CMD: fast and tailored conceptual river and sewer models for integrated water management

CMD : modèles conceptuels rapides et adaptés de la rivière et du réseau pour une gestion intégrée de l'eau

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RÉSUMÉ

En appui de la gestion de l'eau, il faut des modèles efficaces afin d'évaluer et d'optimiser des stratégies différentes au niveau du bassin, de quantifier l'impact des tendances telles que le changement climatique ou l'urbanisation en hausse, et enfin, de prendre en compte plusieurs incertitudes et risques. Pour les gestionnaires de l'eau, les modèles hydrodynamiques sont devenus l'outil standard. Néanmoins, ces modèles présentent des lacunes considérables, dont les principales sont : les temps de simulation très longs, les possibilités d'interfaçage limitées et la caractérisation souvent trop complexe pour les applications visées. Pour cette raison, nous avons développé une nouvelle méthodologie flexible en vue de convertir ces modèles détaillés de la rivière et du réseau en modèles conceptuels. Plusieurs études de cas ont montré que les modèles conceptuels sont entre 10^3 et 10^6 fois plus rapides que les modèles hydrodynamiques classiques, à la suite de la jonction efficace des processus et en s'appuyant sur les structures de modèles avancées. En parallèle, les modèles conceptuels imitent amplement la dynamique complexe des modèles plus détaillés. Un outil logiciel semi-automatique, nommé CMD, a été développé pour configurer rapidement des modèles conceptuels. En conceptualisant deux modèles de réseau détaillés de InfoWorks CS pour les villes de Geel et de Mol, aussi qu'un modèle détaillé en MIKE11 de la rivière Molse Nete, cette communication illustre l'approche de la modélisation et du logiciel.

ABSTRACT

Efficient models are needed in support of water management to evaluate and optimize different strategies on catchment level, quantify the impact of trends such as climate change or the increasing urbanization, and account for various uncertainties and risks. Detailed hydrodynamic models have become the standard tools of water managers. However, these models suffer from several fundamental shortcomings, of which very long simulation times, limited interfacing possibilities and an often overly complex characterization for the intended applications are arguably the main ones. Therefore, we developed a novel flexible framework to translate detailed river and sewer quantity models to lumped conceptual models that can be tailored to a specific purpose. Various case studies showed that these conceptual models are between 10^3 and 10^6 times faster than conventional hydrodynamic models due to the efficient lumping of processes and by relying on advanced model structures, while they emulate the complex dynamics of the more detailed models accurately. A semi-automatic tool, named CMD, was developed to quickly configure conceptual models. This paper illustrates the modelling approach and tool by conceptualizing two detailed InfoWorks CS sewer models for the cities of Geel and Mol, and a detailed MIKE11 model of the Molse Nete River.

KEYWORDS

Calculation speed, conceptual modelling, decision support, software, water management.

1 INTRODUCTION

Water systems are characterized by many interacting processes on different scales. An integrated approach at catchment scale is required that can deal with these interactions to develop effective and sustainable strategies. Due to the inherent complexity of the water system and the broad scope of water management, models are needed to support decision making. These models need to be employable for very diverse analyses, such as optimization questions, uncertainty and risk quantification and impact estimation of trends. Each type of analyses poses specific model requirements. However, water managers rely almost exclusively on detailed hydrodynamic models for designing new strategies or performing analyses of river and sewer systems. Due to their prolonged calculation times, these models cannot be employed for running long term simulations, or for applications that require a large amount of simulations, such as optimization questions or uncertainty analyses. In addition, integration of such detailed models is limited to local scales, and often problematic for technical reasons. Therefore, we propose the complimentary use of simplified or so-called conceptual models besides the conventionally used detailed hydrodynamic models. These conceptual models lump processes and rely on an alternative characterization of the river and sewer systems instead of using the de Saint-Venant equations. Their parsimonious structure results in very short simulation times and facilitates model interfacing, enabling multidisciplinary analyses at catchment scale. These features make conceptual models ideally suited for applications requiring fast and integrated models, while the results could be linked back to hydrodynamic models if spatially detailed investigations are required.

A new, integrated modelling approach is being developed to set up such conceptual models. This framework incorporates a flexible hydrological modelling component that can be efficiently employed at different scales and that delivers consistent results with varying resolution and model detail (Tran and Willems, 2015). In addition, two data-based mechanistic and modular approaches are included, one tailored to river modelling (Wolfs et al., 2015) and another for modelling sewer systems (Wolfs and Willems, 2015). Research is also being done on conceptual water quality modelling for rivers. To ensure that the conceptual models can be configured quickly, a user-friendly tool named Conceptual Model Developer (CMD) has been set up. **Figure 1** schematizes the modelling framework. This paper focuses on the newly developed conceptual modelling methodology for rivers and urban drainage systems.

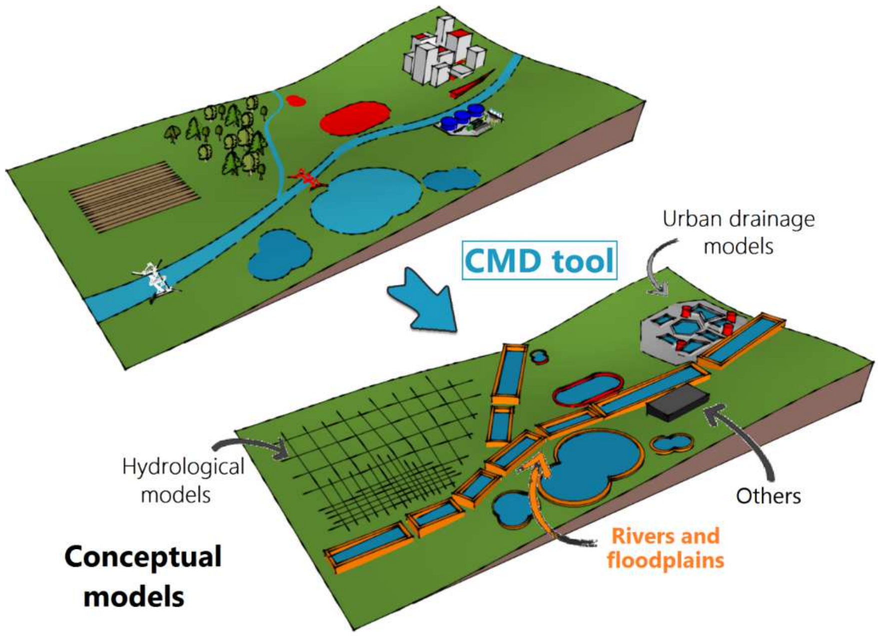

Figure 1: Schematization of the newly developed modelling framework to configure fast and tailored integrated conceptual models using the developed CMD software.

2 CONCEPTUAL MODELLING METHODOLOGY AND SOFTWARE

A new data-driven mechanistic and modular conceptual modelling approach was developed for rivers and sewer systems. The reader is referred to Wolfs et al. (2015) and Wolfs and Willems (2015) for details on the modelling approaches. The main characteristics are briefly discussed in this paragraph.

The conceptual models are derived from data, but most of the parameters are still interpretable in physically meaningful terms. For instance, dikes and hydraulic structures can be modelled explicitly in river systems. Such mechanistic representation is crucial for many scenario analyses and optimization questions. Due to the modularity of the methodology, the modeller can select the most appropriate model structures to emulate the dynamics of the system, including backwater effects and pressurized or reverse flows. Structures that are frequently applied in hydrology, such as the linear reservoir theory and transfer functions, are combined with advanced machine learning techniques such as artificial neural networks, adaptive neuro fuzzy inference systems, M5' model trees and state dependent parameter models. The approach is based on the storage cell concept, which implies that the entire system is divided in multiple interconnected cells. In each cell, the water balance is closed explicitly. Figure 2 shows the topologies of a conceptual river and sewer model. In addition, a new discrete and explicit solver was developed that employs a variable time step that differs in space and time. This solver maximizes computational efficiency and avoids numerical instabilities during simulations. The developed modelling methodology results in flexible, accurate and very fast models that are suitable for many scenario investigations and the optimization of strategies.

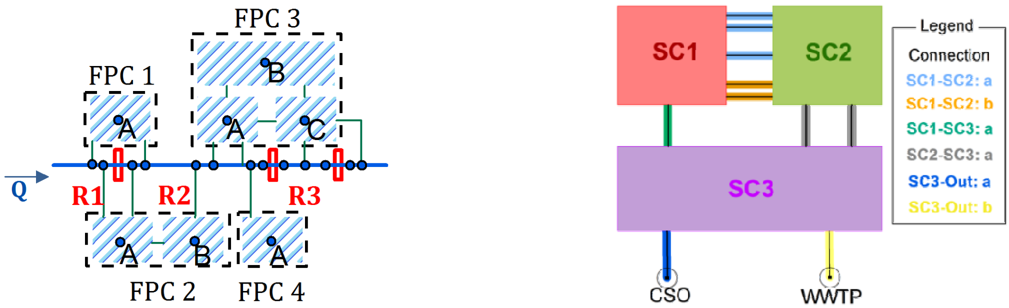

Figure 2: Example of a conceptual model topology for a river with floodplains and hydraulic structures indicated in red (left) and an urban drainage system (right) based on the storage cell concept. The broad gamut of included model structures is used to calculate the variables in the system.

The developed modelling approaches were incorporated in the CMD software tool to facilitate model set-up. Based on the delineated topology of the conceptual model, the tool "learns" how the different elements are interconnected. This enables fully automatic handling of the data sets and calibrated model structures. The tool guides the user through the step-wise calibration. The user can use built-in and tailored algorithms to identify the most suitable model structures. The tool is coded in MATLAB and equipped with GUIs. The models itself are generated in the C programming language to yield the fastest possible models. A close interfacing was foreseen with the InfoWorks and MIKE programs.

3 CASE STUDY AND APPLICATIONS

The functionality of the developed modelling approaches and software is hereafter illustrated based on a case study of the sewer systems of the cities Mol and Geel, and the receiving Molse Nete River. Conceptual models were set up and calibrated to existing full hydrodynamic models of the two sewer systems and the river system and consequently interfaced. The coupled river-sewer model was used to quantify the impact of the combined sewer overflows (CSOs) on the water quality of the receiving river (see Keupers et al., 2015, for more details on the water quality part). For the water quantity part, the main objective of the conceptual models was to predict CSO flows accurately, together with the flows and water levels in the river.

To overcome the lack of sufficient and accurate measurement data, simulation results of the existing full hydrodynamic models were employed. These detailed models were implemented in InfoWorks CS for the two sewer systems and MIKE11 for the river system. For the sewer models, the conceptual models were configured based on simulation results for design storms with return periods ranging between 1/20 and 20 years. For the river model, this was done based on a 1-year long term simulation in the MIKE11 model. These events and time series were chosen to ensure that the most important dynamics are included in the calibration and validation sets. The final conceptual model topology of the two sewer systems is shown in **Figure 3**. The average Nash-Sutcliffe efficiencies (NSE) for the simulated volumes of cells in the conceptual model are 0.81 and 0.94 for the sewer systems of Mol and Geel respectively for all validation events, indicating a good fit. The performance of the conceptual river model is exceptionally good, with NSE values for all simulated flows and stages exceeding 0.985 for all investigated events. Simulating a one-year period with the coupled conceptual river-sewer model takes merely 1.41 seconds, while this takes almost 60 hours with the hydrodynamic models.

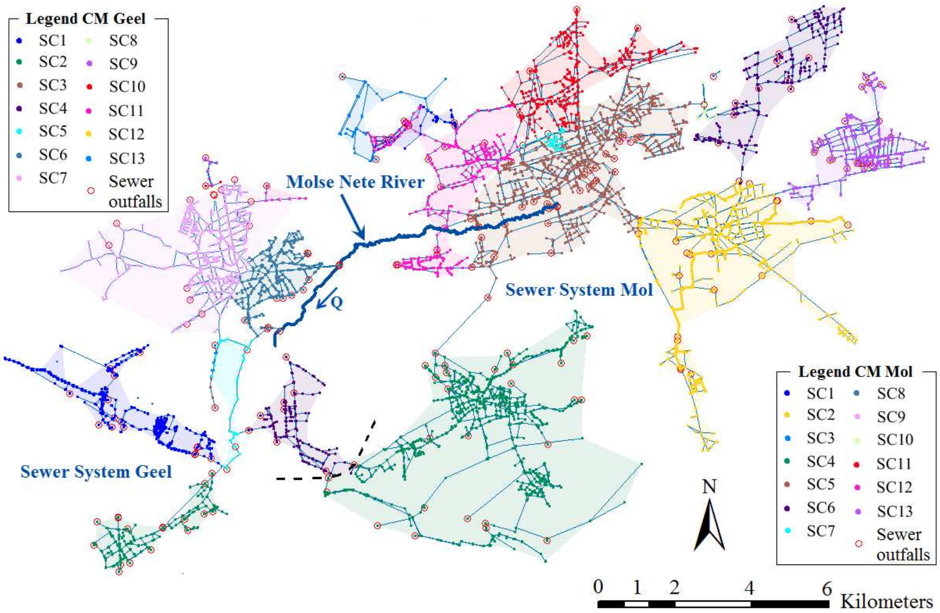

Figure 3: Topology of the conceptual models of the sewer systems of Mol and Geel, together with the modelled segment of the Molse Nete River.

Next to this integrated sewer-river modelling application, the methodology and CMD software were already employed for various other applications. A coupled sewer-river system was created to analyze different urban and river flood mitigation measures (De Vleeschauwer et al., 2014). A conceptual river model at catchment scale is used to control hydraulic structures in real time via model predictive control to reduce flood damage in the Demer basin (Vermuyten et al., 2015). Another conceptual river model was used for flood probability mapping in real time along the Dender River (Wolfs et al., 2012).

4 CONCLUSIONS

A modular and flexible conceptual modelling approach was developed to overcome the limitations of conventionally used detailed hydrodynamic models. Processes can be lumped on different scales. Due to the variety of incorporated model structures, the models can emulate complex dynamics such as backwater effects accurately. The parsimonious model structure and very short calculation times allow model interfacing on larger scales, enabling integrated system analyses. A software tool, named Conceptual Model Developer (CMD), was developed to quickly configure the conceptual models. This tool and modelling approach were demonstrated on a case study by modelling two sewer systems and the receiving river. The integrated conceptual model emulates the simulation results of hydrodynamic models precisely, but simulates events 150 000 times faster than the detailed models. Such short calculation time enables optimization of strategies, accounting for uncertainties and risks and performing long term simulations.

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